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## İzmirAnkara suture as a Triassic to Cretaceous plate boundary – data from central Anatolia

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# Tectonics

## RESEARCH ARTICLE

10.1029/2019TC005849

### Special Section:

Tectonic evolution of West-Central Tethysides

### Key Points:

- Late Triassic, Jurassic, and Late Cretaceous oceanic subduction-accretion complexes exist along the İzmir-Ankara suture
- The İzmir-Ankara ocean has affinity to the wide eastern Tethyan oceans rather than to the narrow and young Balkan and Alpine oceans
- Lower Eocene red beds and regional stratigraphy indicate that the hard continental collision took place in the Paleocene

### Supporting Information:

- Supporting Information S1
- Table S1 New Ar-Ar data.
- Table S2 New U-Pb zircon data.

### Correspondence to:

A. I. Okay,  
okay@itu.edu.tr

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## İzmir-Ankara Suture as a Triassic to Cretaceous Plate Boundary—Data From Central Anatolia

Aral I. Okay<sup>1,2</sup> , Gürsel Sunal<sup>2</sup>, Sarah Sherlock<sup>3</sup>, Andrew R. C. Kylander-Clark<sup>4</sup>, and Ercan Özcan<sup>2</sup>

<sup>1</sup>Eurasia Institute of Earth Sciences, İstanbul Technical University (İTÜ), Ayazağa, İstanbul, Turkey, <sup>2</sup>Faculty of Mines, Department of Geological Engineering, İstanbul Technical University (İTÜ), Ayazağa, İstanbul, Turkey, <sup>3</sup>School of Physical Sciences, STEM Faculty, The Open University, Milton Keynes, UK, <sup>4</sup>Department of Earth Sciences, University of California, Santa Barbara, CA, USA

**Abstract** The İzmir-Ankara suture represents part of the boundary between Laurasia and Gondwana along which a wide Tethyan ocean was subducted. In northwest Turkey, it is associated with distinct oceanic subduction-accretion complexes of Late Triassic, Jurassic, and Late Cretaceous ages. The Late Triassic and Jurassic accretion complexes consist predominantly of basalt with lesser amounts of shale, limestone, chert, Permian (274 Ma zircon U-Pb age) metagabbro, and serpentinite, which have undergone greenschist facies metamorphism. Ar-Ar muscovite ages from the phyllites range from 210 Ma down to 145 Ma with a broad southward younging. The Late Cretaceous subduction-accretion complex, the ophiolitic mélange, consists of basalt, radiolarian chert, shale, and minor amounts of recrystallized limestone, serpentinite, and greywacke, showing various degrees of blueschist facies metamorphism and penetrative deformation. Ar-Ar phengite ages from two blueschist metabasites are ca. 80 Ma (Campanian). The ophiolitic mélange includes large Jurassic peridotite-gabbro bodies with plagiogranites with ca. 180 Ma U-Pb zircon ages. Geochronological and geological data show that Permian to Cretaceous oceanic lithosphere was subducted north under the Pontides from the Late Triassic to the Late Cretaceous. This period was characterized generally by subduction-accretion, except in the Early Cretaceous, when subduction-erosion took place. In the Sakarya segment all the subduction-accretion complexes, as well as the adjacent continental sequences, are unconformably overlain by Lower Eocene red beds. This, along with the stratigraphy of the Sakarya Zone, indicates that the hard collision between the Sakarya Zone and the Anatolide-Tauride Block took place in Paleocene.

**Plain Language Summary** Eurasia and the northern mountain ranges of Turkey, the Pontides, were separated by an ocean or oceans from the central and southern Anatolia, the Anatolide-Tauride Block. The number of the intervening oceans, their age, and their mode of closure are controversial. We provide geological and geochronological data to show that a single İzmir-Ankara ocean separated Eurasia-Pontides from the Anatolide-Block from at least the Permian (ca. 274 Ma) until the Late Cretaceous (ca. 80 Ma) with the İzmir-Ankara ocean subducting north under the Pontides from the Late Triassic (ca. 210 Ma) to the Late Cretaceous (ca. 80 Ma). The Black Sea opened as a back-arc basin in the Late Cretaceous separating the Pontides from the mainland Eurasia. The final closure of the İzmir-Ankara ocean started in the Late Cretaceous (ca. 80 Ma) and finished in the Paleocene (ca. 60 Ma), when the zone of collision became a land area.

## 1. Introduction

A suture can be defined as a tectonic line marking the boundary between two continental margin sequences deposited on opposing sides of a former ocean (e.g., Moores, 1981). It represents a major geological discontinuity and is commonly associated with accretionary complexes, ophiolitic mélanges, and ophiolites, which bear evidence for the duration, subduction, and final closure of the intervening ocean. The İzmir-Ankara suture in Turkey forms part of the Mesozoic boundary between the Laurasia in the north and the Gondwana in the south; the suture continues in the east as the Sevan-Akera suture to the Lesser Caucasus and in the west as the Vardar suture to the Hellenides (Figure 1, Okay & Tüysüz, 1999).

In the Hellenides and in the Alps, the Tethyan oceans opened during the Jurassic through the rifting of the Pangea, whereas in the Middle and Far East a wide Tethyan ocean existed between Laurasia and Gondwana





**Figure 1.** (a) Outcrops of the subduction-accretion complexes, ophiolites, and magmatic arc rocks in western and central Turkey (based on Maden Tetkik ve Arama Genel Müdürlüğü, 2016). (b) Tectonic map of the Eastern Mediterranean-Black Sea region (Okay & Tüysüz, 1999).

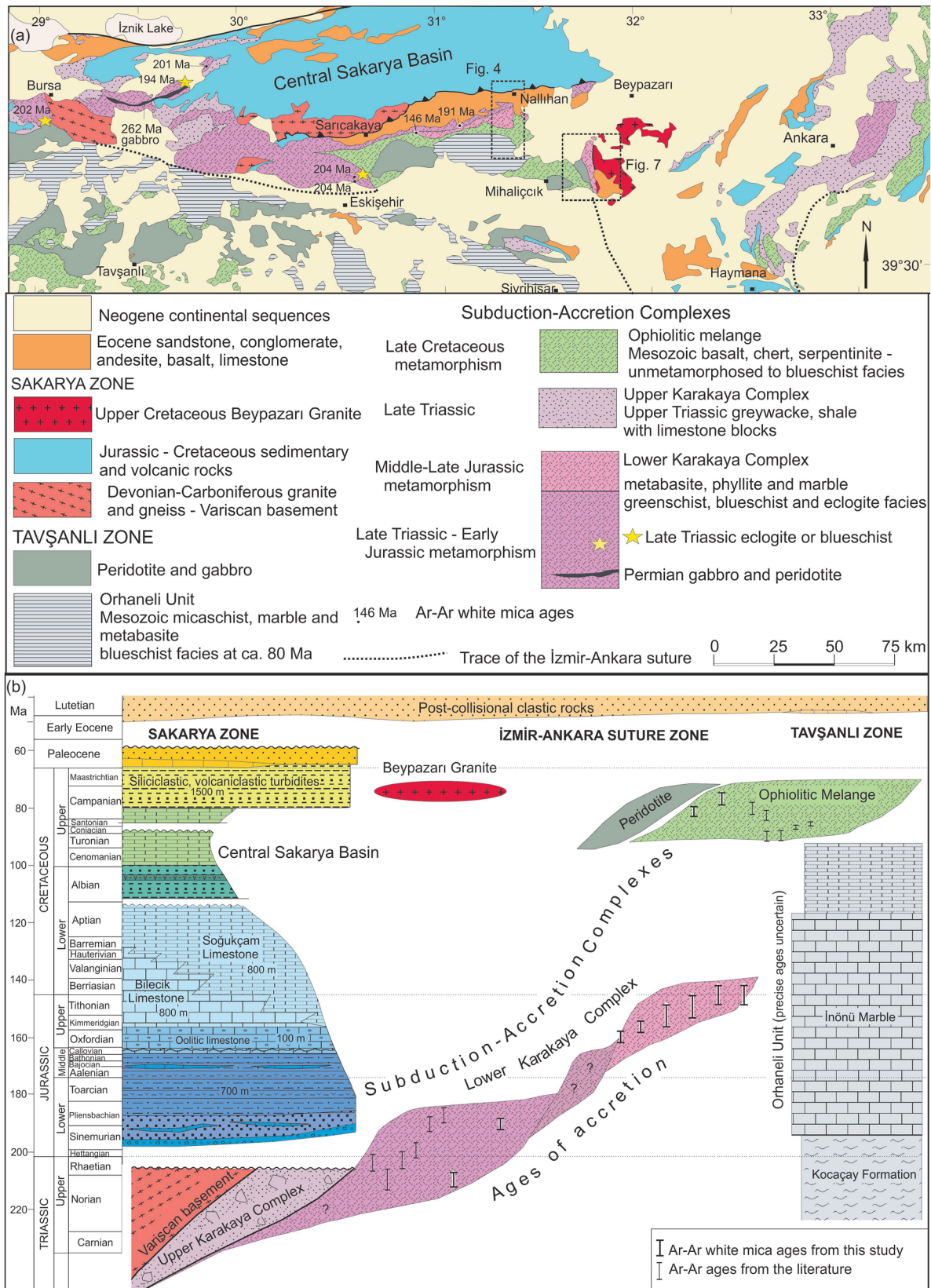
since the Early Paleozoic (e.g., Barrier & Vrielynck, 2008; Schmid et al., 2008). Anatolia is located in the region of transition between the relatively narrow Jurassic Neo-Tethys oceans in the west and a wide, long-ranging Paleozoic-Mesozoic Tethys in the east. The early plate tectonic models of Anatolia envisaged a Western Alps type scenario, where the Pontides rifted away from the Anatolide-Tauride Block during the Early Jurassic followed by the generation of a Jurassic northern Neo-Tethyan ocean, namely, the İzmir-Ankara ocean (e.g., Şengör & Yılmaz, 1981). However, geological studies in Anatolia in the last 20 years showed that the İzmir-Ankara ocean was in existence at least since the Permian (Okay, 2000; Tekin et al., 2002; Topuz et al., 2013). The new data brought up several other questions such as the age of the opening of the İzmir-Ankara ocean, the nature of subduction, for example, episodic or continuous, and the periods of accretion and subduction-erosion. A suitable segment of the İzmir-Ankara suture to address such questions is the well-exposed suture zone along the Sakarya River in the Central Anatolia west of Ankara (Figure 1). We mapped and studied this Sakarya segment of the İzmir-Ankara suture with the aim of understanding the history of the suture and that of the associated Tethyan ocean.

## 2. Geological Setting

In northwest Turkey the Laurasia is represented by the Sakarya Zone of the Pontides. Prior to the opening of the Black Sea in the Late Cretaceous, the Sakarya Zone was located south of the East European Platform. It is separated by the İzmir-Ankara suture from the Tavşanlı Zone of the Anatolide-Tauride Block, which was part of Gondwana before the early Mesozoic opening of the Eastern Mediterranean and Bitlis-Zagros ocean (e.g., Şengör & Yılmaz, 1981). The Sakarya Zone consists of a pre-Jurassic basement overlain unconformably by a Jurassic to Tertiary sedimentary and volcanic succession (Figure 2). The pre-Jurassic basement consists of two parts: (a) high-grade metamorphic rocks and intrusive Carboniferous granites, representing a Variscan crystalline basement (Kibici et al., 2010; Topuz et al., 2020; Ustaömer et al., 2012), and (b) an Upper Triassic oceanic subduction-accretion complex, the Karakaya Complex. The Karakaya Complex is subdivided into two parts: an upper part consisting of highly deformed Upper Triassic sandstones with exotic Permian and Carboniferous limestone blocks and a lower part made up of Permo-Triassic metabasites, locally with tectonic lenses of blueschists and eclogites with Late Triassic metamorphic ages (Okay & Göncüoğlu, 2004). The Lower Karakaya Complex is regarded as an oceanic plateau or a series of oceanic islands accreted to the southern margin of Laurasia during the Late Triassic (Okay, 2000; Pickett & Robertson, 2004). The Upper Karakaya Complex is unconformably overlain by Lower Jurassic continental to shallow marine conglomerates and sandstones (Figure 2, Altın et al., 1991), which pass up into a thick succession of Middle Jurassic to Lower Cretaceous limestones (Figure 2). The Albion-Cenomanian is represented by deep marine volcanoclastic sandstones and limestones, which are overlain by Turonian to Santonian pelagic limestones. An abrupt change occurs in the Campanian, when pelagic carbonate sedimentation is succeeded by the deposition of thick clastic turbidites with tuff horizons (Ocakoglu et al., 2019). The turbidites form a regressive sequence and pass up into Paleocene molassic sandstones and conglomerates (Figure 2).

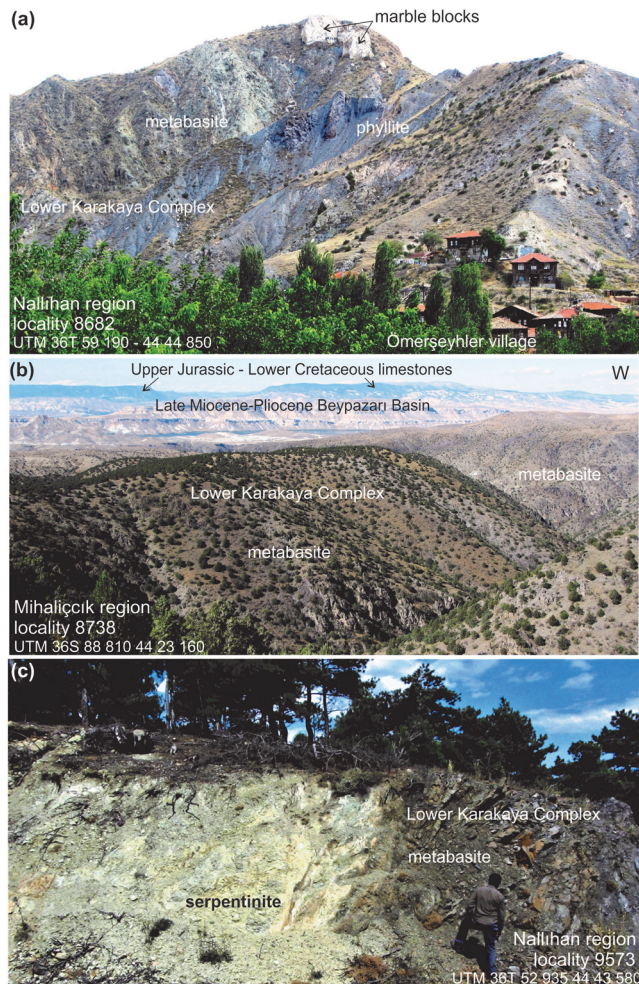
The Tavşanlı Zone south of the İzmir-Ankara suture constitutes the subducted northern margin of the Anatolide-Tauride Block. It is subdivided into a lower continental and an upper oceanic unit. The continental unit, called as the Orhaneli Unit, consists of micaschists with Ordovician metagranitoids overlain by a thick sequence of Mesozoic marbles (Figure 2). The whole sequence has undergone a blueschist facies metamorphism at 440 °C and 21 Kbar with widespread development of jadeite, lawsonite, and sodic amphibole (Okay & Whitney, 2010; Plunder et al., 2015). Phengite Ar-Ar and Rb-Sr ages from the Orhaneli Unit cluster at around 80 Ma (Sherlock et al., 1999). The Orhaneli Unit is tectonically overlain by ophiolitic mélange consisting of basalt, radiolarian chert, pelagic shale, and minor serpentinite and limestone. The ophiolitic mélange has undergone variable degrees of blueschist metamorphism (Okay & Whitney, 2010). Northwest of Sivrihisar the ophiolitic mélange is represented by lawsonite-eclogites and associated garnet-lawsonite metabasites (Çetinkaplan et al., 2008; Davis & Whitney, 2006). Ar-Ar phengite ages from the Sivrihisar blueschists and lawsonite-eclogites range from 90 to 80 Ma (Purteau et al., 2019; Sherlock et al., 1999).

The ophiolitic mélange is tectonically overlain by large Upper Cretaceous ophiolite slabs. The ophiolite slabs consist predominantly of peridotite with minor gabbro and are cut by isolated diabase dykes. Locally there are slices of garnet-amphibolite at the base of the peridotites (Okay et al., 1998; Plunder et al., 2016). The



**Figure 2.** (a) Geological map of the İzmir-Ankara suture between Balıkesir and Ankara (based on Aksay et al., 2002; Konak, 2002; Turhan, 2002; Türkecan & Yurtsever, 2002). (b) Stratigraphy of the tectonic units at the İzmir-Ankara suture zone.





**Figure 3.** Photographs of the Lower Karakaya Complex. (a) Metabasite and phyllite with marble blocks in the Nallıhan region. (b) Metabasites in the Mihaliçcik region. (c) Serpentinite and metabasite in the Nallıhan region. For location of the photographs see Figure 4.

oldest sedimentary sequence, which lies unconformable over the continental and oceanic units, is Lower-Middle Eocene clastic rocks with shallow marine limestone horizons (Figure 2, Konak, 2002).

### 3. Methods

Methods employed during this study include geological mapping, biostratigraphy, and Ar-Ar and U-Pb geochronology. Geological mapping was done on 1:25,000 scale topographic maps. The locations of samples and observation points are given in UTM coordinates on European 1978 basis. Mineral separation was done in the Istanbul Technical University using classical techniques including crushing, sieving, and magnetic separation. For zircon separation we used sodium polytungstate as a heavy liquid. The zircons were picked under a stereographic microscope and mounted in epoxy and were polished. Zircons were analyzed using laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at the University of California, Santa Barbara. For the details of the method employed, see Kylander-Clark et al. (2013) and Okay et al. (2014). Long-term reproducibility in secondary reference materials is <2% and, as such, should be used when comparing ages obtained within this analytical session to ages elsewhere. Micas were dated using the Ar-Ar single-grain fusion method at the Open University in the United Kingdom. For the details of the method see Okay et al. (2014). The Ar-Ar and U-Pb analytical data are given in supporting information Tables S1 and S2, respectively.

### 4. İzmir-Ankara Suture Zone

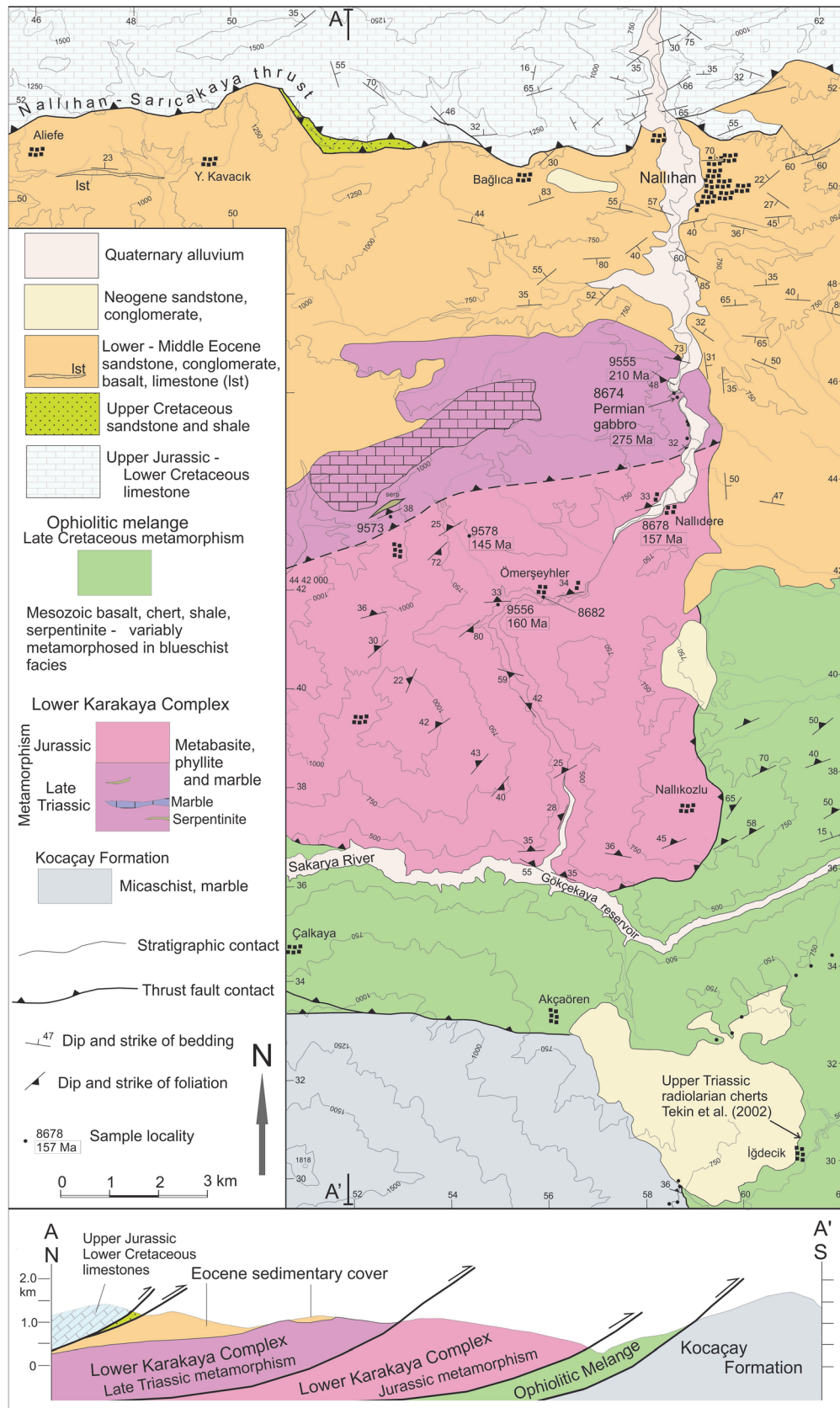
We mapped and studied two segments of the İzmir-Ankara suture zone in northwest Turkey (Figure 2). The first segment in the Nallıhan region forms part of a south-vergent Eocene fold and thrust belt, and the second segment in the Mihaliçcik region has an unusual north-south trend imposed by a major shear zone (Figures 1 and 2). Subduction-accretion complexes and continental sequences in these regions are described below.

#### 4.1. Subduction-Accretion Complexes

Late Triassic-Jurassic and Late Cretaceous subduction-accretion complexes are exposed in the Nallıhan and Mihaliçcik regions, representing distinct periods of accretion to the southern margin of Laurasia.

##### 4.1.1. Late Triassic-Jurassic Subduction-Accretion-Lower Karakaya Complex

The Lower Karakaya Complex is made up of metabasite, marble, and phyllite/micaschist with lesser amounts of metachert, metadiorite, metagabbro, and serpentinite (Figure 3). In northwest Turkey the Lower Karakaya Complex forms a 220-km-long east-west trending belt extending from Bursa to Nallıhan (Figure 1). The metabasites are the dominant lithology (65% of the outcrops) in both the Nallıhan and Mihaliçcik regions followed by dark phyllites/micaschists (30%) with minor marble, metagabbro, serpentinite, and metachert; serpentinite forms thin tectonic slivers in the metabasites (Figure 3c). The rocks show a distinctive foliation and are cut by large number of shear zones and faults; the sequence represents a thrust stack rather than a regular stratigraphic series. The metamorphism is in greenschist facies with the development of actinolite + albite + chlorite + epidote in the metabasic rocks and muscovite + quartz + chlorite  $\pm$  garnet in the micaschists/phyllites. Grade of metamorphism, although in greenschist facies, varies among different tectonic slices; fine-grained metaclastic rocks are generally represented by phyllites, with micaschists restricted to a few tectonic slices. Göncüoğlu et al. (2000) also report sodic amphibole from the metabasites in the Nallıhan region. With its lithology and structure the Lower Karakaya Complex represents a subduction-accretion complex. In the Nallıhan and Mihaliçcik areas it is unconformably overlain by Lower-Middle Eocene red beds with volcanic flows (Figure 4).



**Figure 4.** Geological map and cross section of the Nallıhan region. For location see Figures 1 and 2.



**Table 1**  
*Summary of the New Age Data*

Unit	Rock type	Sample no.	Location (UTM coordinates)	Dated mineral	Method	Age (Ma)	Stratigraphic age	
Karakaya Complex	Nallıhan	Metagabbro	8674	36T 03 58 925 - 44 45 703	Zircon	U-Pb	275.4 ± 3.3	Early Permian
Karakaya Complex	Nallıhan	Micaschist	9555	36T 03 58 685 - 44 46 095	Muscovite	Ar-Ar	209.8 ± 1.8	T3 - Norian
Karakaya Complex	Nallıhan	Micaschist	10358	36T 03 58 334 - 44 43 497	Muscovite	Ar-Ar	191 ± 1.1	J1 - Sinemurian
Karakaya Complex	Nallıhan	Metadiorite	8678	36T 03 58 334 - 44 43 494	Muscovite	Ar-Ar	156.6 ± 0.9	J3 - Kimmeridgean
Karakaya Complex	Nallıhan	Micaschist	9556	36T 03 58 334 - 44 43 495	Muscovite	Ar-Ar	159.5 ± 1.2	J3 - Oxfordian
Karakaya Complex	Nallıhan	Micaschist	9578	36T 03 51 630 - 44 42 960	Muscovite	Ar-Ar	145.4 ± 3.6	J3 - Tithonian
Karakaya Complex	Sarıcakaya	Micaschist	10366	36T 03 19 212 - 44 35 605	Muscovite	Ar-Ar	145.6 ± 2.6	J3 - Tithonian
Karakaya Complex	Mihaliçcik	Phyllite	8745	36S 03 90 724 - 44 19 613	Muscovite	Ar-Ar	153.0 ± 3.0	J3 - Kimmeridgean
Karakaya Complex	Mihaliçcik	Micaschist	8835	36S 03 91 825 - 44 29 010	Muscovite	Ar-Ar	150.1 ± 4.1	J3 - Kimmeridgean
Ophiolitic melange	Mihaliçcik	Gabbro	8773	36S 03 83 834 - 44 12 507	Zircon	U-Pb	179.8 ± 3.9	J1 - Toarcian
Ophiolitic melange	Mihaliçcik	Micaschist	9867A	36S 03 90 257 - 44 13 332	Phengite	Ar-Ar	82.7 ± 1.0	K2 - Campanian
Ophiolitic melange	Mihaliçcik	Zoisite-micaschist	9916	36S 03 84 600 - 44 14 076	Phengite	Ar-Ar	78.2 ± 1.6	K2 - Campanian
Ophiolitic melange	Mihaliçcik	Greywacke	10175	36S 03 88 704 - 44 12 438	Zircon	U-Pb	215–2,186	Detrital zircons
Beypazarı Granite	North outcrop	Granite north	9022	36S 03 97 433 - 44 15 167	Zircon	U-Pb	74.6 ± 0.6	K2 - Campanian
Beypazarı Granite	South outcrop	Granite south	10098	36S 03 92 138 - 44 13 675	Zircon	U-Pb	73.2 ± 1.4	K2 - Campanian
Beypazarı Granite	South outcrop	Granite west	10171	36S 03 93 594 - 44 11 402	Zircon	U-Pb	74.5 ± 0.5	K2 - Campanian
Beypazarı Granite	North outcrop	Granite	9456 <sup>a</sup>	36S 03 92 580 - 44 24 571	Zircon	U-Pb	74.8 ± 0.4	K2 - Campanian
Beypazarı Granite	North outcrop	Granite	8823 <sup>a</sup>	36S 03 97 333 - 44 20 720	Zircon	U-Pb	73.7 ± 0.4	K2 - Campanian
Beypazarı Granite	North outcrop	Granite	8823	36S 03 97 333 - 44 20 720	Biotite	Ar-Ar	79.2 ± 0.9	K2 - Campanian
Beypazarı Granite	North outcrop	Granite	8817	36S 03 98 271 - 44 14 850	Biotite	Ar-Ar	80.1 ± 1.4	K2 - Campanian

Note. The UTM coordinates are in European 1979 grid. For full analytical data see Tables S1 and S2 in the supporting information.

<sup>a</sup>From Okay et al. (2019).

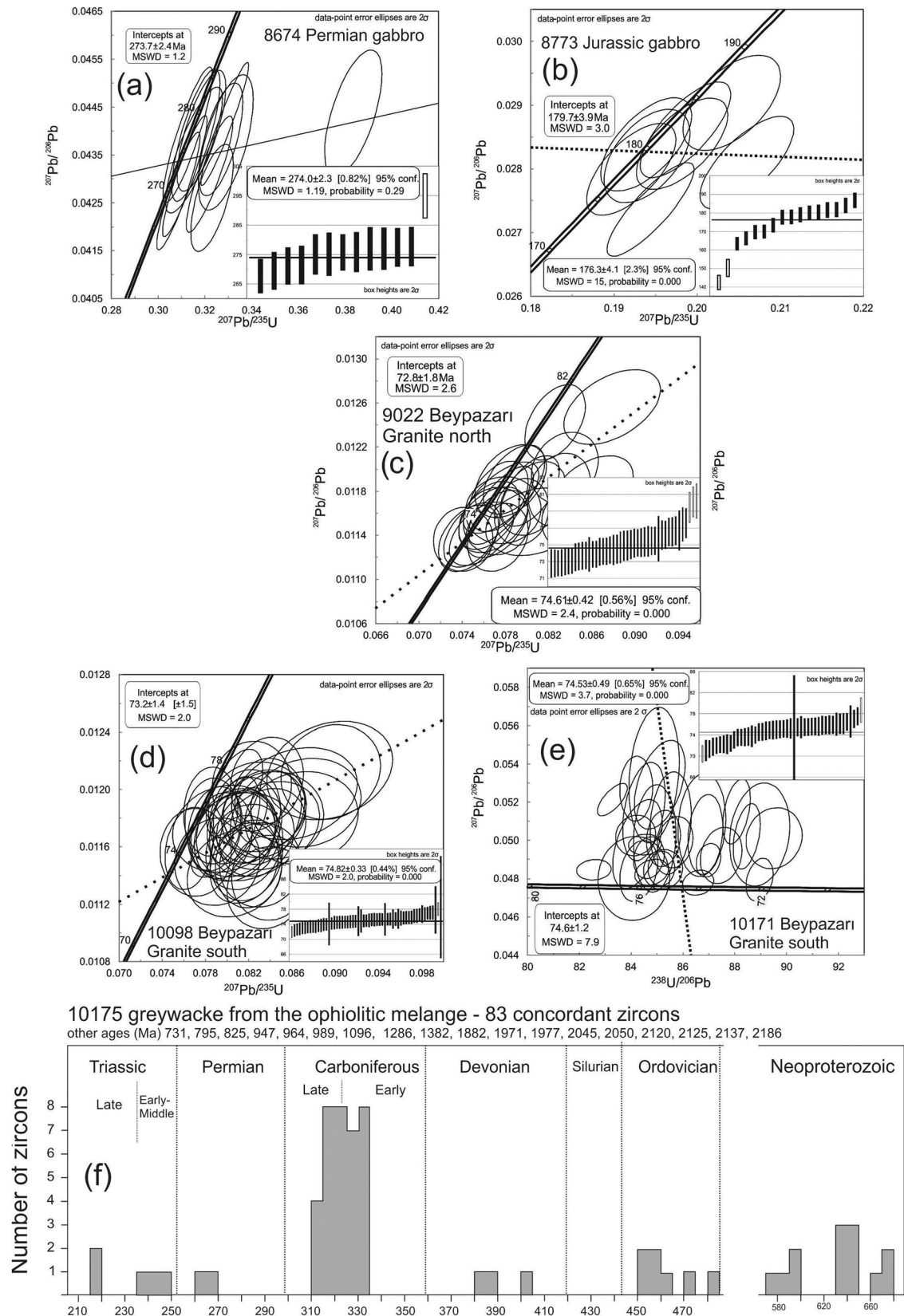
To constrain the age of metamorphism white micas from eight micaschist/phyllite samples are dated using the single-grain fusion Ar-Ar laser probe technique. Two samples are from Mihaliçcik, four from Nallıhan, and two from Sarıcakaya west of Nallıhan (Figure 2). The Ar-Ar ages range from 210 Ma (Late Triassic) down to 145 Ma (latest Jurassic) (Tables 1 and S1). In the Nallıhan region the Triassic age comes from the northern and the Jurassic ages from the southern part of the Lower Karakaya Complex, whereas in the Mihaliçcik region the Ar-Ar ages are all Jurassic (Figure 4). There is an apparent lack of Ar-Ar ages between 190 and 160 Ma, which could be due to incomplete sampling. The Ar-Ar ages suggest 70 Myr of subduction/metamorphism and accretion between the Late Triassic and the Late Jurassic; published metamorphic ages from the Lower Karakaya Complex in northwest Turkey range from Late Triassic to Early Jurassic (Figure 2, Okay & Monié, 1997; Okay et al., 2002; Topuz et al., 2018); the new data extend the age to the Late Jurassic.

The age of the subducting oceanic lithosphere in the Lower Karakaya Complex is constrained by dating zircons from a metagabbro (sample 8674 in Figure 4). The metagabbro and serpentinite forms a 10-m-large tectonic slice within the metabasites. The metagabbro has undergone a greenschist facies metamorphism and consists of actinolite, albite, clinozoisite, and muscovite. Twelve zircon grains produced a middle Permian U-Pb age of  $273.7 \pm 5.5$  Ma (Figure 5a and Table S2). The age is similar to the age of another disrupted metaophiolite (ca. 262 Ma) described recently from the Lower Karakaya Complex in the Bursa region, 160 km farther east (Figure 2a, Topuz et al., 2018) and indicates that the Late Triassic subduction involved middle Permian oceanic lithosphere.

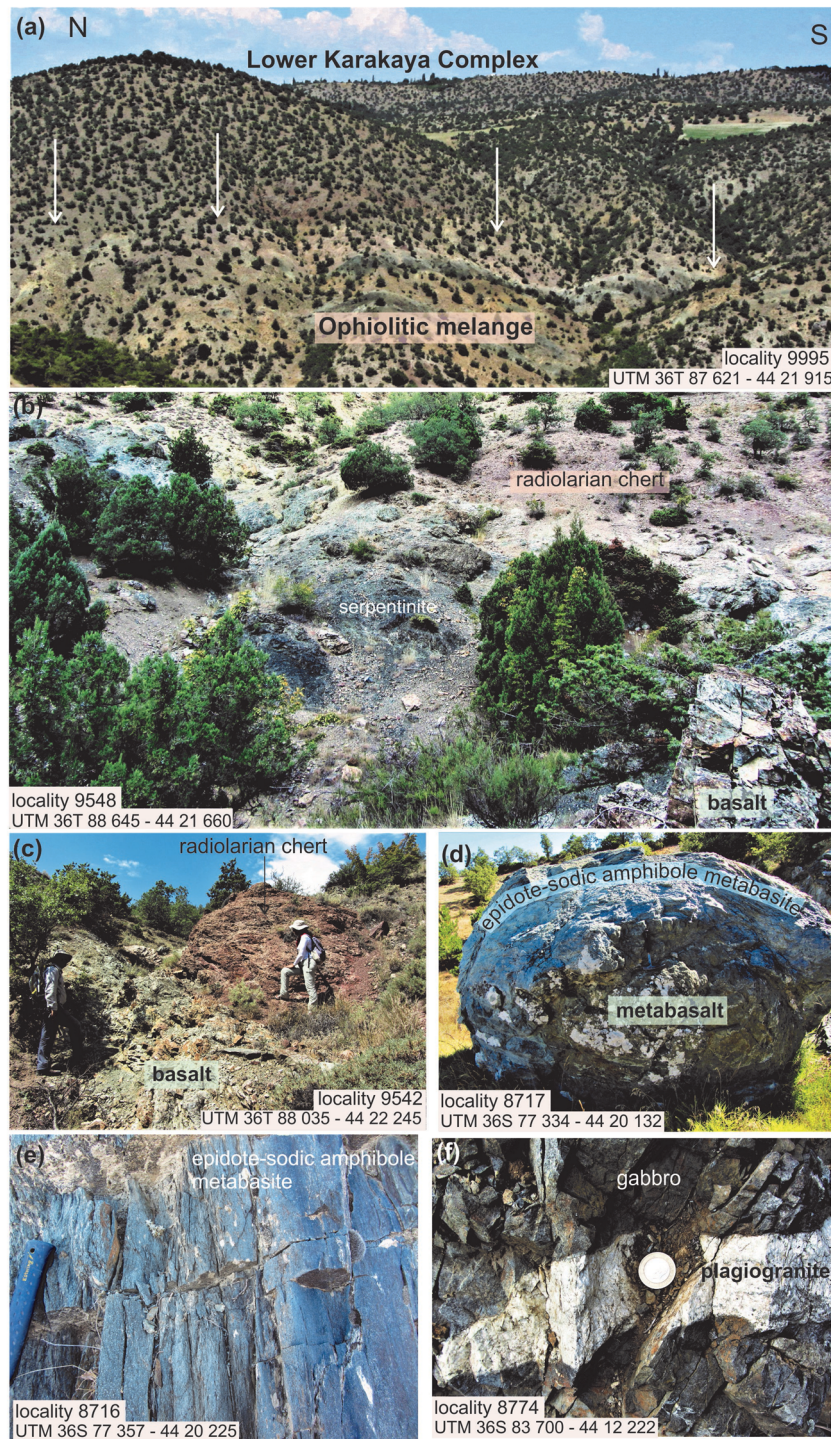
#### 4.1.2. Ophiolitic Mélange-Late Cretaceous Subduction-Accretion

The ophiolitic mélange consists, in decreasing order of abundance, of basalt, radiolarian chert, greywacke, pelagic shale, serpentinite, and limestone and their metamorphic equivalents (Figure 6). These oceanic lithologies are tectonically juxtaposed with no clearly defined matrix and are associated with large peridotite bodies (Figure 7). The ophiolitic mélange is readily distinguished from the Karakaya Complex by its variegated lithologies, which leads it to be known also as colored mélange. In the ophiolitic mélange, basalts are the most abundant lithology making up more than 80% of the outcrops, followed by radiolarian chert, pelagic shale, and serpentinite (Figures 6a–6c). A geochemical study of the basalts in the ophiolitic mélange in the Nallıhan-Sarıcakaya region has suggested a wide variety of tectonic environments including mid-ocean ridge, oceanic island, and back-arc basin (Göncüoğlu et al., 2006). Radiolaria from red cherts





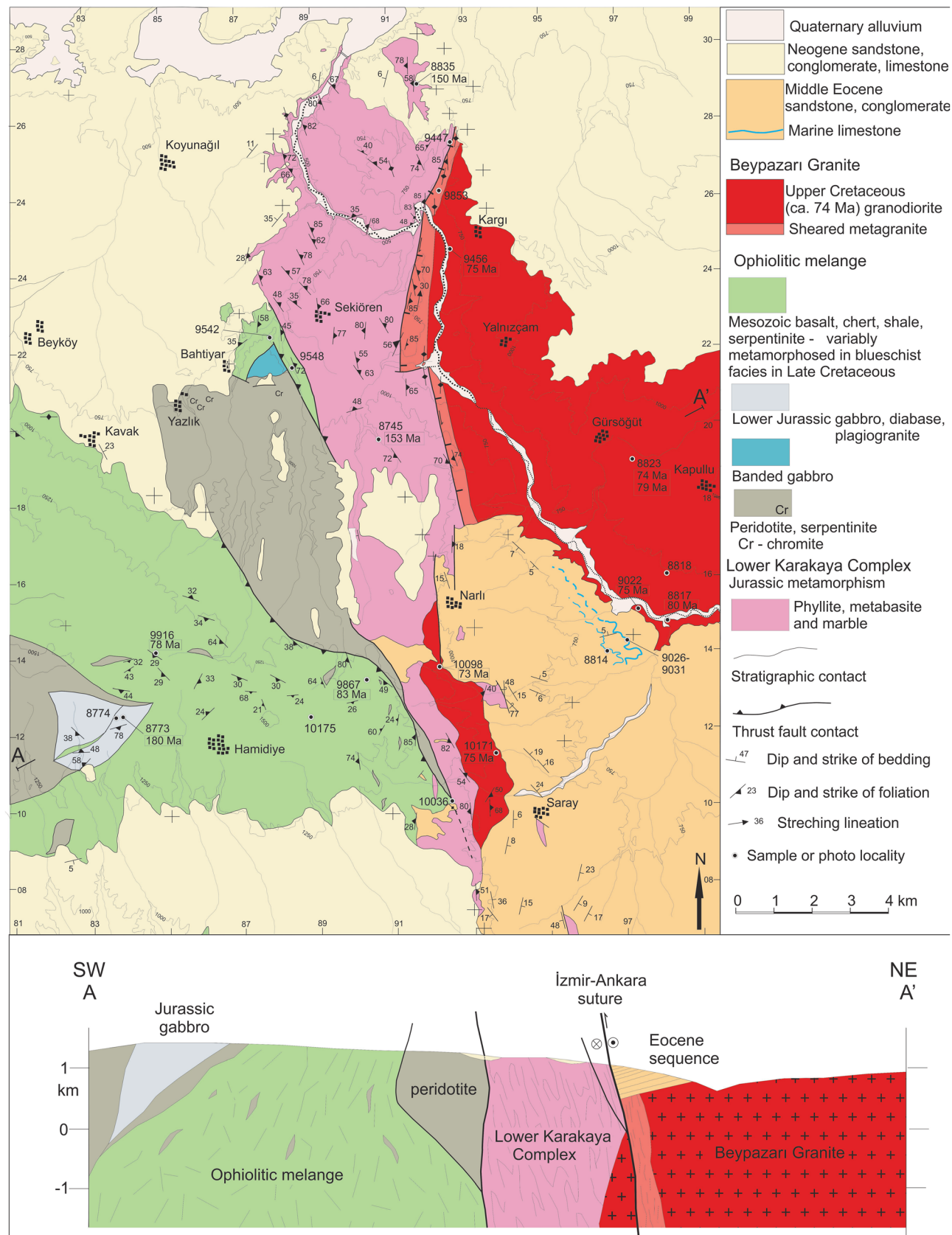
**Figure 5.** Zircon U-Pb concordia diagrams from the Permian metagabbro in the Lower Karakaya Complex (a), from the Jurassic gabbro, from the ophiolitic mélangé (b), from the Beypazari Granite (c–e), and histograms of detrital zircons from the greywacke in the Upper Cretaceous ophiolitic mélangé.



**Figure 6.** Photographs of the ophiolitic mélangé from the Mihaliçcik region. (a) The subvertical fault contact between the Lower Karakaya Complex and the ophiolitic mélangé. (b) Red radiolarian chert, serpentinite, and basalt. (c) Red radiolarian chert and basalt, the two most common rock types in the ophiolitic mélangé. (d) An incipiently metamorphosed basalt is rimmed by foliated blueschist metabasite. (e) Foliated blueschist metabasites. (f) Jurassic plagiogranite vein in gabbro. For location of the photographs see Figure 7.

associated with the basalts in the Nallıhan-Sarıcakaya region have been dated as Late Triassic (Carnian), Middle-Late Jurassic (Bathonian-Tithonian), and Early Cretaceous (Hauterivian-Aptian and Cenomanian) (Göncüoğlu et al., 2000, 2006; Tekin et al., 2002).





**Figure 7.** Geological map and cross section of the Mihalççık region. For location see Figures 1 and 2.

Metamorphism and penetrative deformation are highly variable in the ophiolitic *mélange*; the rocks range from well-foliated blueschist facies metabasites to undeformed basalts over distances of as short as a few hundred meters (Figures 6c–6e); however, even in undeformed basalts, high pressure metamorphic minerals such as lawsonite and sodic pyroxene are common. Contacts between differently deformed and metamorphosed units are constituted by shear zones.

Over 100 samples from the ophiolitic *mélange* were examined petrographically. The common mineral assemblage in the metabasites is sodic amphibole + epidote + albite + chlorite + phengite + calcite (Çoğulu, 1967). Lawsonite bearing metabasites occur close to the western peridotite or as enclaves within the peridotite. These rocks largely preserve their igneous texture and igneous augite.

To constrain the age of the blueschist metamorphism, phengites from two metabasite samples (9868 and 9916) were dated using Ar-Ar method; the ages are  $78.2 \pm 1.6$  Ma and  $82.7 \pm 1.0$  Ma (Tables 1 and S1) and indicate oceanic subduction and metamorphism during the Campanian. These ages are similar to those obtained earlier from the Tavşanlı Zone (Sherlock et al., 1999).

Most subduction-accretion complexes, such as the Makran Complex in Iran and Pakistan, and the Franciscan Complex in California, are dominated by turbiditic sandstones and shales representing trench sediments derived from the coeval magmatic arc. In contrast, the ophiolitic *mélanges* along the İzmir-Ankara suture are mainly made up of oceanic crustal rocks principally of basalt, shale, and radiolarian chert. In the Mihaliççık-Nallıhan areas sandstones make up less than 3% of the ophiolitic *mélange*. However, they are important in providing information on the source region. Detrital zircons from a sandstone sample (10175) from a 15-m-thick greywacke-shale slice enclosed in the basalts in the ophiolitic *mélange* in the Mihaliççık region were dated; 111 detrital zircons were analyzed of which 83 are concordant at 90–110% level. The ages are shown in Figure 5f, and the analytical data are given in Table S2. The detrital zircons show a wide variety of ages ranging from Paleoproterozoic to Triassic (Figure 5f). The dominant group are Carboniferous zircons (35 zircons, 42% of the total zircon population) followed by Precambrian (30 grains, 36% of the zircon population), Ordovician (7 grains), and Triassic (5 grains) zircons with a few Devonian and Permian zircons (Figure 5f). Significantly, there are no Jurassic or Cretaceous zircons. There are no records of a coeval arc magmatism in the detrital zircon data. This explains the scarcity of greywackes in the ophiolitic *mélange* and shows that the ophiolitic *mélange* represents a sediment-starved accretionary complex. The Late Cretaceous subduction zone was intra-oceanic and was separated from the magmatic arc by a stretch of supra-subduction oceanic crust, which prevented the arc-detritus reaching the subduction zone.

#### 4.1.3. Ultramafic and Gabbro Bodies in the Ophiolitic *Mélange*

Small (<100 m) serpentinite slices in the ophiolitic *mélange* make up about 5% of the outcrops; there are also two large peridotite-gabbro bodies embedded in the ophiolitic *mélange* in the Mihaliççık region (Figure 7). The eastern one, which crops out over an area 10 km by 3.5 km, consists predominantly of harzburgite and dunite with a small gabbro body in its northeastern corner. Repeated attempts to extract zircon from the gabbro did not produce results. The dunite includes economic chromite lenses and layers exploited close to the Bahtiyar village.

The second peridotite-gabbro tectonic slice in the west is surrounded by the ophiolitic *mélange*. The peridotite shows strong serpentinization and silicification; a body of gabbro crops out along the eastern margin of the peridotite. The gabbro consists of hornblende and plagioclase and shows compositional banding on centimeter to millimeter scale. It is cut by plagiogranite veins with thicknesses of 1 cm to 5 m (Figure 6f). Fourteen zircon grains from the plagiogranite produced an Early Jurassic U-Pb age of  $179.8 \pm 3.9$  Ma (Figure 5b and Table S2). A similar zircon U-Pb age of  $179 \pm 15$  Ma was obtained from a plagiogranite dyke cutting dolerites in the ophiolitic *mélange* northeast of Ankara (Dilek & Thy, 2006).

## 4.2. Continental Crustal Sequences

The units deposited or formed on continental crust comprise the Jurassic and younger sedimentary series of the Central Sakarya Basin, the Upper Cretaceous Bepazarı Granite, and part of the Tavşanlı Zone.

### 4.2.1. Jurassic and Younger Sequence of the Central Sakarya Basin-Sakarya Zone

The sedimentary sequence of the Central Sakarya Basin crops out in the hangingwall of the Nallıhan-Sarıcakaya thrust north of Nallıhan (Figures 2 and 4). The stratigraphy of the Central Sakarya

Basin is well known and extends from the Early Jurassic to Paleocene (Figure 2, Altın et al., 1991; Altınlı, 1976; Ocakoğlu et al., 2019; Saner, 1980). It starts with Lower Jurassic conglomerates and sandstones, which rest unconformably over the Upper Karakaya Complex or over the Carboniferous granites. The Lower Jurassic clastic rocks are overlain by Upper Jurassic-Lower Cretaceous limestones, which crop out on the hangingwall of the Nallıhan-Sarıcakaya thrust (Figure 4). The limestones are in turn overlain by a thick sequence of Upper Cretaceous (Campanian-Maastrichtian) siliciclastic turbidites with volcanic horizons. The turbidites form a regressive series and pass up gradually into continental red beds of Paleocene age.

The Nallıhan-Sarıcakaya thrust corresponds to a major paleogeographic boundary; in the hangingwall of the thrust the sedimentary sequences extend from Early Jurassic to Paleocene, whereas on the footwall the metamorphic basement with Jurassic metamorphic ages is overlain by Eocene sediments.

#### 4.2.2. Tavşanlı Zone Sequences

South of Nallıhan the ophiolitic mélangé is structurally underlain by gray, banded gneissose micaschists, which pass up into a thick sequence of white marble. The micaschists have a structural thickness of more than 2 km and are composed of quartz, white mica, chlorite, and albite. The micaschist sequence and the overlying marbles can be correlated with the Kocaçay Formation and İnönü Marble, respectively, which represents the subducted Mesozoic sequence of the Tavşanlı Zone (Okay & Whitney, 2010). South of Bursa the Kocaçay Formation has a probable Triassic depositional age (Bozkurt et al., 2019) and has undergone blueschist facies metamorphism with the development of jadeite and glaucophane in the micaschists. The apparent absence of high-pressure minerals in the micaschists south of Nallıhan is possibly related to retrogression.

#### 4.2.3. The Beypazarı Granite-Late Cretaceous Pluton

In the Mihaliçcik region, the Lower Karakaya Complex is intruded by a large Upper Cretaceous pluton, the Beypazarı Granite (Figure 7). The Beypazarı Granite is a coarse-grained, hornblende and biotite bearing granodiorite with a calc-alkaline composition and a geochemistry similar to that of the magmatic arc plutons (Figure 8b, Helvacı et al., 2014; Öztürk et al., 2012; Speciale et al., 2014).

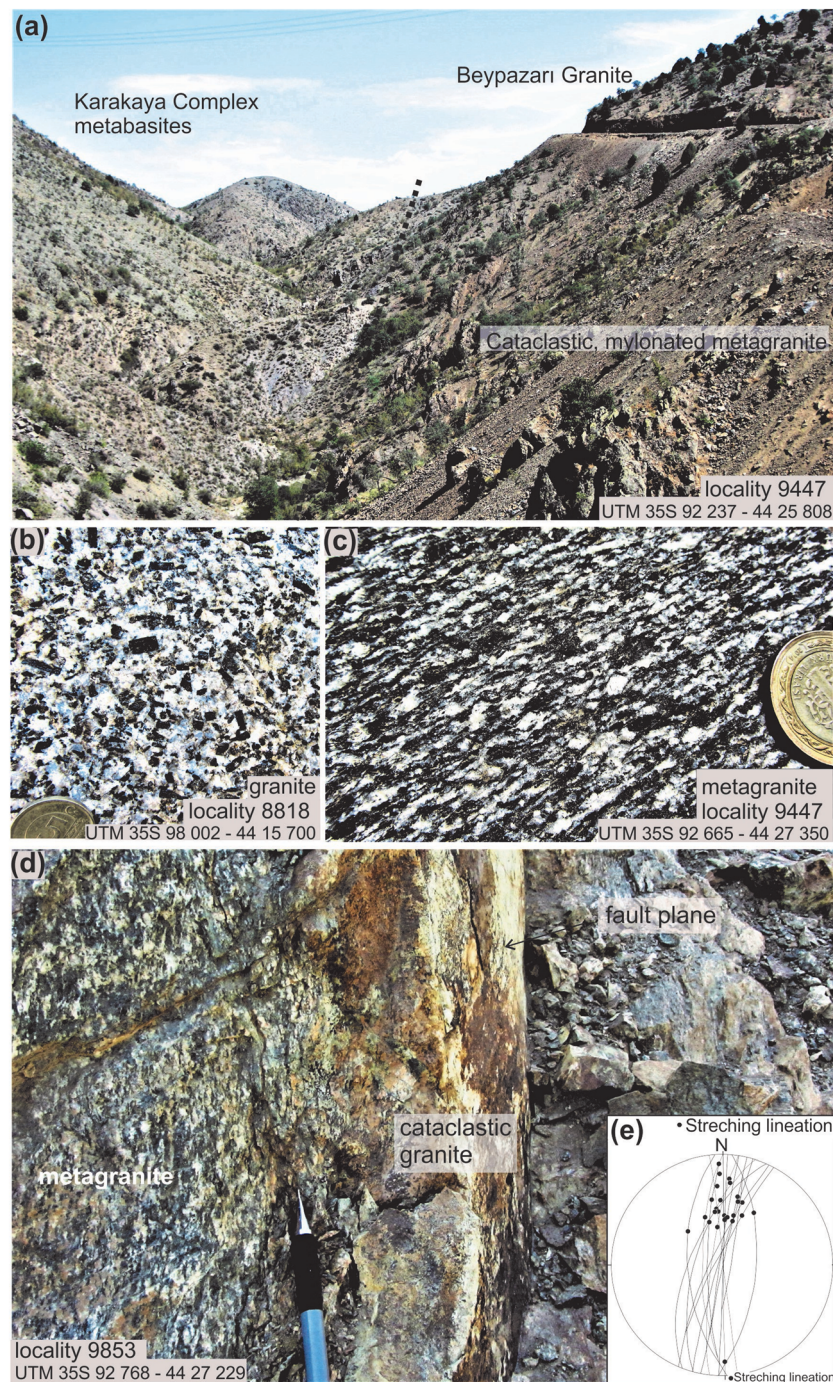
Helvacı et al. (2014) report zircon Pb-Pb evaporation ages from four samples of the Beypazarı Granite ranging from 79 Ma down to 73 Ma, and Okay et al. (2019) provided U-Pb laser ablation ICP-MS ages from two samples (8823 and 9456) of  $73.7 \pm 0.4$  Ma and  $74.8 \pm 0.4$  Ma, respectively. In the region studied the outcrops of the granite are divided in two patches through an intervening Eocene cover (Figure 7). In the northern outcrop the contact between the Beypazarı Granite and the Karakaya Complex is a north-south shear zone, whereas an intrusive contact is preserved in the south. The southern granite is medium-grained, porphyritic with zoned plagioclase crystals indicating a shallower level of emplacement; to test whether both outcrops of the granite are of the same age, zircons from two samples from the southern granite and one sample from the northern granite were dated using laser ablation ICP-MS. The sample from the northern granite (9022) yielded an age of  $74.6 \pm 0.6$  (Figure 5c and Table S2), and two samples from the southern granite (10098 and 10171) gave ages of  $73.6 \pm 1.4$  Ma and  $72.9 \pm 1.2$  Ma, respectively (Figures 5d and 5e and Table S2). The age data show that both outcrops of the granite are part of the same plutonic body, which was emplaced during the Late Cretaceous (late Campanian,  $74 \pm 2$  Ma) in the Karakaya Complex.

Biotites from two samples (8817 and 8823) from the Beypazarı Granodiorite were also dated by Ar-Ar technique to constrain its cooling history. The laser probe Ar-Ar ages are 80 and 79 Ma and are unusual in that they are slightly older than the recrystallization ages; nevertheless, they indicate fast cooling and hence uplift following the crystallization of the granite. Hornblende K-Ar ages of 75–71 Ma from the Beypazarı Granite reported by Helvacı et al. (2014) also point to fast cooling. The Beypazarı Granite is unconformably overlain by Eocene sandstones and conglomerates.

#### 4.3. Sakarya Shear Zone

A major part of the contact between the Lower Karakaya Complex and the Beypazarı Granite is constituted by a north-south trending transpressive shear zone (Figures 7 and 8). This Sakarya Shear Zone developed mostly in the granitic rock is up to 300 m thick. Within the shear zone the granitic rocks show a strong mylonitic foliation, banding, and locally a stretching lineation, which dips at low angles to the north (Figure 8). Quartz in the mylonites shows recrystallization into fine-grained aggregates forming quartz ribbons, whereas feldspar and hornblende show semi-brittle deformation and commonly form porphyroclasts (Figure S1). Such textural features indicate that the mylonitization in the present structural levels have





**Figure 8.** Photographs from the Sakarya Shear Zone. (a) The contact between the metabasites of the Lower Karakaya Complex and the cataclastic, mylonated granites of the Beypazari pluton. Undeformed (a) and deformed (c) Beypazari Granite. (d) Beypazari Granite with a steeply dipping mylonitic foliation overprinted by a brittle fault. (e) Lower hemisphere equal area projection of the mylonitic foliation and lineation in the granites in the Sakarya Shear Zone. For locations see the map in Figure 7.

formed at temperatures of about 400 °C (e.g., Passchier & Trouw, 1998, p. 48). Overall, the mylonitic foliation dips east at 80°, and the stretching lineation plunges north at 25–48° (Figure 8e). Brittle structures, including micro-faults, have locally overprinted the mylonitic fabric (Figure 8d). Striations along such fault planes also show an oblique orientation dipping to the north. Micro-textures such as the rotation of feldspar



porphyroclasts and biotite mica fish (Figure S1) indicate a right-lateral and reverse sense of movement showing that the Sakarya Shear Zone has a dextral transpressive character.

## 5. Post-collisional Eocene Sequence—The Kızılçay Formation

The tectonic units of the Sakarya and Tavşanlı zones are unconformably overlain by a predominantly continental Eocene sequence. In the Mihaliçcik region, a 500-m-thick Eocene sequence of fluvial sandstone, mudstone, and minor conglomerate with rare horizons of shallow marine sandy limestone, called the Kızılçay Formation, lies unconformably over the Beypazarı Granite, the Lower Karakaya Complex, and the ophiolitic mélange (Figure 7). The first marine strata with a rich fauna of large benthic foraminifera are found ~60 m above the Beypazarı Granite (Figure 7). The foraminifera include *Alveolina kieli*, *Alveolina tenuis*, *Alveolina* cf. *delicatissima*, *Alveolina orhaniyensis*, *Discocyclina radians*, *Discocyclina fortisi*, *Discocyclina dispansa*, and *Nemkovella* sp. and indicate an early Middle Eocene (early Lutetian, shallow benthic zone SBZ 13) age. Thus, by ca. 48 Ma, the Beypazarı Granite, the Lower Karakaya Complex, and the ophiolitic mélange were tectonically juxtaposed and amalgamated. The Eocene age also constrains the main activity of the Sakarya Shear Zone between 74 and 48 Ma (Campanian-Middle Eocene).

In the Nallıhan region, the Kızılçay Formation includes basaltic and andesitic lava flows and rare marine limestone beds. Zircon and Ar-Ar ages from the volcanic rocks are Early to Middle Eocene (Ypresian-Lutetian, 52–45 Ma, Kasapoğlu et al., 2016; Şahin et al., 2019). Shallow benthic foraminifera from the limestone beds include *Nummulites discorbinus*-*N. beaumonti* group, *N. ex. gr. perforatus*, *N. ex. gr. mill-ecaput*, *Assilina* sp., *Alveolina* sp., and *Sphaerogypsina* sp. The fauna indicates a middle-late Lutetian age (SBZ14-16).

The Kızılçay Formation crops out as a 115-km-long narrow belt south of the Nallıhan-Sarıcakaya thrust (Figure 2). It has formed as a continental foreland fold and thrust belt due to flexural loading by the Nallıhan-Sarıcakaya thrust (Mueller et al., 2019). West of Nallıhan the Kızılçay sequence is apparently completely continental with volcanic and volcanoclastic rocks dated between 52.4 and 48.0 Ma (Mueller et al., 2019).

## 6. Discussion

### 6.1. Subduction From Late Triassic to Late Cretaceous

Preservation of subduction-accretion complexes of distinct ages is common in active margins, such as in the Franciscan Complex in California (e.g., Wakabayashi, 2015). The ages of the subduction-accretion complexes generally show an oceanward younging, as also observed in the Nallıhan-Mihaliçcik region. The duration of subduction can be determined from the ages of the subduction zone metamorphism and from the age of the magmatic arcs. The new Ar-Ar metamorphic ages from the accretionary complexes in the Nallıhan-Mihaliçcik region indicate subduction from the Late Triassic to Jurassic (210–145 Ma) and in the Late Cretaceous (90–75 Ma, Turonian-Campanian) along the İzmir-Ankara subduction zone. Early Cretaceous could have been a period of shallow subduction and/or subduction erosion, which left no record (Table 2).

Late Triassic (215–201 Ma) eclogites and blueschists are known from the Lower Karakaya Complex in north-west Turkey (Okay et al., 2002; Okay & Monié, 1997; Topuz et al., 2018); the new ages extend the subduction into the Jurassic (Figure 9). Late Cretaceous subduction-accretion is well known from other parts of the İzmir-Ankara suture (e.g., Rojay, 2013; Sarifakioglu et al., 2014; Yılmaz, 2017). There is comparatively less data on Jurassic subduction-accretion; Çelik et al. (2011) describe amphibolites from the ophiolitic mélange north of Ankara with Jurassic Ar-Ar amphibole ages (two samples, 177 and 167 Ma). Jurassic metamorphic rocks crop out widely in the southern part of the Central Pontides (Figure 1).

Early Cretaceous subduction-accretion complexes are not known along the İzmir-Ankara suture in western Anatolia, and Early Cretaceous granites and detrital zircons are virtually absent in the Pontides (Akdoğan et al., 2017). However, farther east in the Central Pontides, Early Cretaceous (Albian) eclogites and blueschists are common (Aygül et al., 2016; Okay et al., 2018). The absence of Early Cretaceous subduction-accretion complexes in the western Anatolia can be explained by subduction-erosion due to flat

**Table 2**  
*Major Tectonic Events Along the İzmir-Ankara Suture*

Period/epoch	Major tectonic events
Permian	Pontides located on the southern margin of Laurasia. A wide Tethyan ocean (İzmir-Ankara ocean) exists south of the Pontides/Laurasia during the Permian. Generation of Permian (274–262 Ma) oceanic lithosphere in this İzmir-Ankara ocean. Northward subduction of the İzmir-Ankara ocean under Laurasia/Pontides in the Late Permian.
Triassic	Northward subduction of the İzmir-Ankara ocean throughout the Triassic. Arc magmatism throughout the Triassic; the Triassic arc is located subsurface north of the Black Sea and is known chiefly from the detrital zircon ages in the Triassic trench sandstones. A major subduction-accretion event occurs in the latest Triassic (ca. 200 Ma) with the subduction and partial accretion of a major oceanic plateau to the southern margin of the Pontides/Laurasia (the Karakaya Complex).
Jurassic	Northward subduction continues through the Jurassic. Arc magmatism in the Pontides during most of Jurassic; only diminishes toward the end of the Jurassic. Subduction-accretion continues to the Early Jurassic up to ca. 190 Ma. Generation of Jurassic (ca. 180 Ma) oceanic lithosphere in the İzmir-Ankara ocean.
Early Cretaceous	Subduction-erosion during the first half of the Early Cretaceous (145–120 Ma). No arc magmatism or subduction-accretion during the first half of the Early Cretaceous (145–120 Ma). A major subduction-accretion event in the second half of the Early Cretaceous (112–99 Ma) in the Central Pontides—accretion of oceanic islands and seamounts to the southern margin of Laurasia/Pontides.
Late Cretaceous	Subduction and built-up of a sediment starved subduction-accretion complex, namely, the ophiolitic melange (94–80 Ma). Arc magmatism (90–72 Ma) throughout the Pontides and beyond. Generation of supra-subduction zone oceanic lithosphere (ca. 92 Ma). Separation of the Pontides from the Laurasia with the formation of the oceanic Black Sea back-arc basin (ca. 85 Ma). Continental subduction of the Anatolide-Tauride Block and ophiolite obduction (ca. 80 Ma). Inception of collision between the Pontide arc and the Anatolide-Tauride Block (ca. 76 Ma). The zone of collision raises above sea level; however, marine conditions persist farther north (ca. 65 Ma).
Paleocene-Eocene	Lower Eocene red beds (56–48 Ma) cover and seal the İzmir-Ankara suture.

subduction, a common phenomenon along the active and presumably in ancient subduction zones (e.g., Stern, 2011).

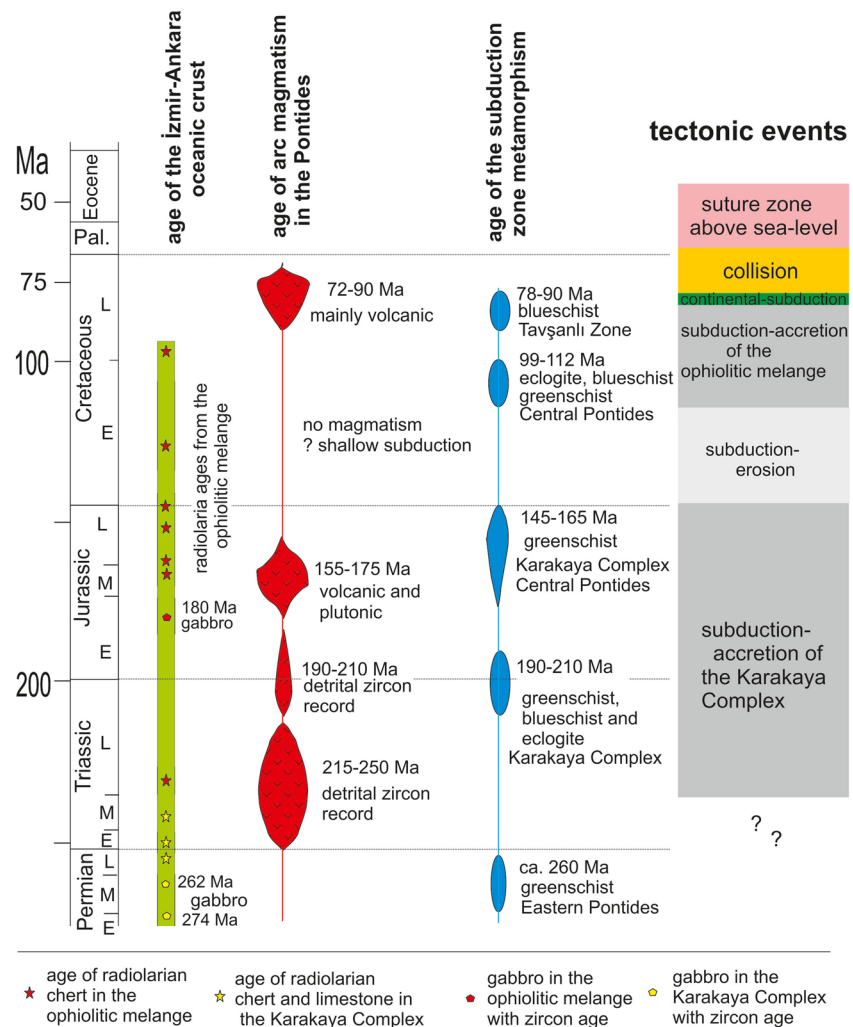
Jurassic (172–158 Ma) and Late Cretaceous (93–74 Ma) magmatic arcs are prominent in the Pontides (Okay & Nikishin, 2015), whereas there are virtually no Triassic arc-related magmatic rocks (Figure 9), despite the fact that the dominant detrital zircon population in the Triassic subduction-accretion complexes and in the Jurassic sandstones are Triassic in age (Akdoğan et al., 2018; Ustaömer et al., 2016). This is explained by the presence of a subsurface Triassic magmatic arc presently located north of the Black Sea (Okay & Nikishin, 2015). Before the Late Cretaceous opening of the Black Sea as a back-arc basin, the Pontides were adjacent to Laurasia and were receiving detritus from this inferred Triassic arc and from the Archean-Paleoproterozoic basement of the East European Platform (Akdoğan et al., 2018).

Fore-arc basins fed by magmatic arcs constitute an integral part of the accretionary subduction, although they may get destroyed later during periods of subduction-erosion. The Upper Triassic-Lower Jurassic turbidites with abundant Triassic detrital zircons in the Central Pontides and in Crimea, the Akgöl and Tauric formations, have been interpreted as fore-arc deposits (Okay et al., 2018; Okay & Nikishin, 2015). The Jurassic volcanoclastic rocks of the Pontides were mostly deposited in a fore-arc basins (Akdoğan et al., 2018). The fore-arc deposition was interrupted during the Early Cretaceous by the subduction-erosion and started again during the Late Cretaceous (Campanian, e.g., Ocakoğlu et al., 2019).

Thus, data from subduction zone metamorphism, magmatic arcs, and fore-arcs indicate northward subduction of the Tethys ocean below the Pontides at least from the Late Triassic to Late Cretaceous (Figure 9 and Table 2).

## 6.2. Age of Subducting Oceanic Crust

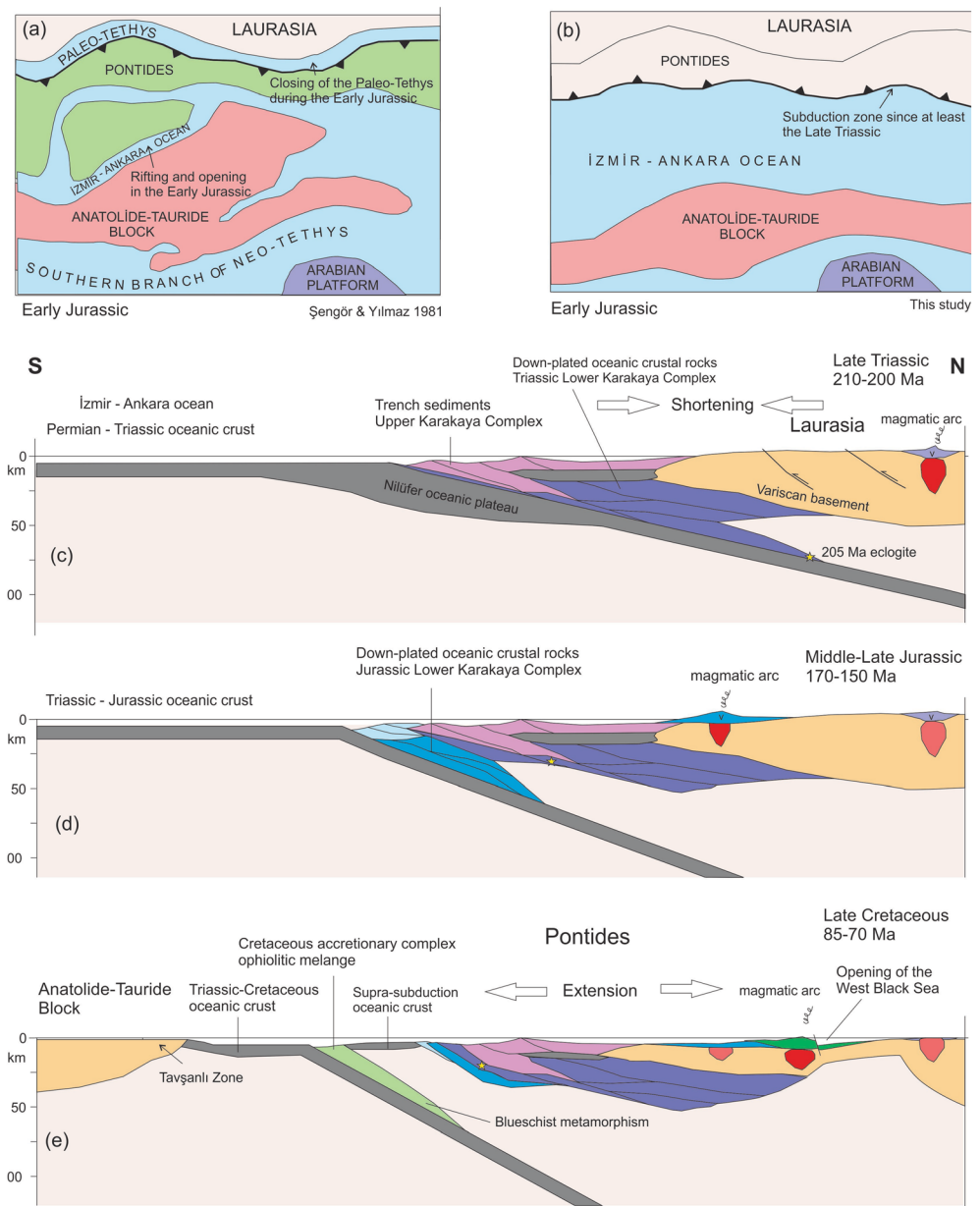
The age of the subducting oceanic lithosphere can be deduced from the age of the dismembered ophiolites and pelagic sedimentary rocks in the subduction-accretion complexes. U-Pb zircons ages from gabbros in the Late Triassic subduction-accretion complexes (the Lower Karakaya Complex) from the Nallıhan region (ca.



**Figure 9.** Data on the age of oceanic crust, arc magmatic rocks, subduction zone metamorphism, and major tectonic events along the İzmir-Ankara suture. For sources of data see the text.

275 Ma) and from north of Bursa (ca. 262 Ma, Figure 2) indicate that Permian oceanic lithosphere was subducting during the Late Triassic (Figures 9 and 10c). Blocks of Middle-Late Devonian, Carboniferous, Upper Permian, and Lower Triassic radiolarian cherts have been described from the Upper Karakaya Complex (Kozur & Kaya, 1994; Kozur et al., 1996; Okay et al., 2011; Okay & Mostler, 1994). Recrystallized limestones within the metabasites of the Lower Karakaya Complex in northwest Anatolia contain conodonts dated to Early and Middle Triassic (Kaya & Mostler, 1992; Kozur et al., 2000). Thus, possibly Devonian to Middle Triassic and certainly Early Permian to Middle Triassic oceanic lithosphere was being subducted during the Late Triassic under the Pontides (Figure 10c). The long age range of the subducting slab could be due to oblique subduction and/or long duration of subduction. For example, Jurassic to Eocene oceanic lithosphere is subducting presently along the Sunda trench because of oblique convergence (e.g., Widiyantoro & van der Hilst, 1996).

The Upper Cretaceous subduction-accretion complexes are represented by ophiolitic mélangé. Red ribbon cherts are a typical and characteristic member of the ophiolitic mélangé. Radiolaria in the cherts in the Nallıhan-Sarıcakaya region has yielded Late Triassic (Carnian), Middle-Late Jurassic (Bathonian-Tithonian), and Early Cretaceous (Berriasian-Hauterivian and Cenomanian) ages (Göncüoğlu et al., 2000, 2006; Tekin et al., 2002). In western and Central Anatolia the radiolaria ages from cherts in the ophiolitic mélanges also range from Late Triassic (Carnian and Norian) to Late Cretaceous (Cenomanian) with most of the stages represented (Bortolotti et al., 2018; Bragin & Tekin, 1996). Lower



**Figure 10.** (a, b) Sketch maps showing respective locations of the Tethyan oceans and continental units in the Early Jurassic according to Şengör and Yılmaz (1981) and the present study, respectively. (c) Collision and accretion of the Nilüfer oceanic plateau to the southern margin of Laurasia. (d) Continuing subduction and accretion during the Jurassic; in the Early Cretaceous, subduction-erosion removed most of the Jurassic subduction-accretion complex. (e) Late Cretaceous subduction-accretion. The subduction was extensional and led to the opening of the West Black Sea basin as a backarc. The eventual closure of the İzmir-Ankara ocean resulted in to the subduction of the continental margin of the Anatolide-Tauride Block.

Cretaceous (Aptian-Barremian) limestones are described associated with pillow lavas in the ophiolitic mélangé near Ankara (Rojay et al., 2004). Thus, Upper Triassic to Upper Cretaceous oceanic lithosphere was subducting during the Late Cretaceous north under the Pontides (Figure 10e).

### 6.3. Was Okeanos Monogamous? Paleotethys Versus Neotethys

Early models of the Tethyan evolution of Anatolia invoked a Cimmerian continent, which separated from Gondwana in the Early Jurassic and moved north, opening Neo-Tethys in its wake and closing Paleo-Tethys in its front (Figure 10a). Eventual collision of the Cimmerian continent with Laurasia in the

Early Jurassic led to the closure of the Paleo-Tethys (e.g., Şengör et al., 1984; Şengör, 1985). However, the juxtaposition of the Late Triassic-Jurassic and Late Cretaceous subduction-accretion complexes without an intervening Cimmerian continent indicates that a scenario involving a Cimmerian continent is not correct (Figure 1, Okay, 2000; Topuz et al., 2013). A simple model of continuous northward subduction of the Tethys ocean under the Pontides from the Late Triassic to the Late Cretaceous is compatible with the data (Figure 10 and Table 2). A similar scenario of continuous subduction from Middle Jurassic to Neogene with episodic accretion is inferred for the generation of the Franciscan Complex (Wakabayashi, 2015). Although northward subduction of the İzmir-Ankara ocean was continuous, accretion was episodic with major accretion episodes in the Late Triassic-Jurassic and Late Cretaceous interspersed with episodes of subduction-erosion possibly during the Early Cretaceous and transform-type boundary during the early Late Cretaceous (Okay et al., 2019). Thus, the İzmir-Ankara suture represents the trace of a Tethyan ocean, which was in existence at least from the Late Triassic to the latest Cretaceous. During the Early Jurassic and later it was accompanied by the Bitlis-Zagros ocean, which separated the Anatolide-Tauride Block from the Arabian Platform (Figure 10b).

#### 6.4. How to Draw a Suture?

Sutures represent lines separating continental margin sequences deposited on the opposing sides of a former oceanic lithosphere; in the case of a wide ocean, the depositional sequences on its opposite sides will be sufficiently different to allow a precise mapping of the suture line. The active margin of a continent commonly expands toward the ocean through accretion of subduction complexes, as happened in the Makran or in California. A similar situation is observed in the Sakarya Zone, where the Upper Triassic-Jurassic subduction-accretion complexes, the Karakaya Complex, was accreted to the Variscan basement and was stratigraphically overlain by Jurassic and younger sedimentary sequences (Figure 2).

During the Late Cretaceous continental subduction/obduction, the ophiolitic mélange was thrust southward over the Anatolide-Tauride Block for several hundred kilometers. Therefore, the İzmir-Ankara suture cannot be delineated on the basis of the distribution of the subduction-accretion complexes or ophiolites, since these could be found up to 500 km south of the boundary of the Sakarya Zone and the Anatolide-Tauride Block (Figure 1). On the other hand, the Phanerozoic sequences of the Sakarya Zone and that of the Anatolide-Tauride Block are distinctly different and allow precise delineation of the suture line.

#### 6.5. Sakarya Shear Zone—Age and Total Offset

In the Central Anatolia, the İzmir-Ankara suture makes a major southward bend (Figure 1); the deflection of the suture was initially mapped based on the displacement of the sequences belonging to the Sakarya Zone (e.g., Okay & Tüysüz, 1999). Our study shows for the first time that the deflection is caused by the transpressive Sakarya Shear Zone. The main activity of the Sakarya Shear Zone is constrained between 75 and 48 Ma (Campanian-Early Eocene) by the age of the Beypazarı Granite and that of the Eocene sedimentary cover. The Sakarya Shear Zone probably formed during the Paleocene continental collision as a major transfer fault.

#### 6.6. Collision Between the Pontide Magmatic Arc and the Anatolide-Tauride Block

The collision between a magmatic arc and a passive margin is a prolonged and complex process lasting between 20 and 50 Myr (e.g., Brown et al., 2011). It starts when the distal parts of the passive margin enter the subduction zone (soft collision) and end with the uplift and erosion of the collision zone (hard collision).

The distal margin of the Anatolide-Tauride Block entered the subduction zone in the early Campanian (ca. 80 Ma) as indicated by the Ar-Ar ages from the Tavşanlı Zone (e.g., Sherlock et al., 1999). The continuing subduction of the continental crust led to the termination of the arc magmatism at the end of the Campanian and to the uplift of the fore-arc basin. The siliciclastic turbidites of the fore-arc (the Central Sakarya Basin) form a regressive sequence and pass up into Maastrichtian shallow marine sandstones and to Early-Middle Paleocene red beds (Saner, 1980). In the Central Sakarya Basin the transition from the marine to continental sedimentation is time transgressive; it occurs in the latest Maastrichtian in the south and in the middle Paleocene in the north. Continental to shallow marine Lower Eocene (56–48 Ma) sequences lie unconformably over both the Pontide and the Anatolide-Tauride units sealing the İzmir-Ankara suture (Mueller et al., 2019). The shortening between the Anatolide-Tauride Block and the Pontides continued after the initial collision as demonstrated by the post-Ypresian Sarıcakaya-Nallıhan thrust (Figure 2a); however, it



did not lead to major crustal thickening and erosion because a major part of shortening was taken up by subduction in the Bitlis-Zagros ocean, the precursor of the Eastern Mediterranean. Thus, the collision between the Pontides and the Anatolide-Tauride Block started in the Campanian (ca. 80 Ma, soft collision) and was completed in the Paleocene (ca. 60 Ma, hard collision).

## 7. Conclusions

1. The İzmir-Ankara suture zone in the Central Anatolia includes Upper Triassic-Jurassic (the Lower Karakaya Complex) and Upper Cretaceous (the ophiolitic mélange) subduction-accretion complexes, which are tectonically juxtaposed without an intervening continental crustal sequence indicating northward subduction of the Tethys ocean under the Pontides from the Late Triassic to the Late Cretaceous.
2. Ar-Ar white mica ages indicate that the subduction-related greenschist facies metamorphism in the Lower Karakaya complex is Late Triassic to Late Jurassic (210–145 Ma), whereas the blueschist facies metamorphism in the ophiolitic mélange is Late Cretaceous (83–78 Ma). The metamorphism of the Lower Karakaya Complex, regarded as latest Triassic (Okay & Göncüoğlu, 2004), is shown to extend into the Late Jurassic. The new data show that there is not a single age for the metamorphism of the Lower Karakaya Complex, as expected from continuous subduction-accretion.
3. The Upper Triassic-Jurassic and Upper Cretaceous subduction-accretion complexes are lithologically distinctive. The Lower Karakaya Complex is dominated by basalt followed by shale and limestone, whereas basalt and red ribbon chert are the two common rock types in the ophiolitic mélange followed by serpentinite and shale. The Lower Karakaya Complex has undergone a greenschist facies metamorphism and the ophiolitic mélange blueschist facies metamorphism.
4. New U-Pb zircon data show the presence of Permian (ca. 274 Ma) metagabbros in the Lower Karakaya Complex; this along with other paleontological data indicates that Devonian to Triassic oceanic lithosphere was subducting northward under the Pontides during the Late Triassic-Jurassic. The ophiolitic mélange includes plagiogranites with Lower Jurassic (ca. 180 Ma) U-Pb ages and Triassic to Upper Cretaceous radiolarian cherts indicating subduction of Late Triassic to Late Cretaceous (Carnian to Cenomanian, ca. 230–95 Ma) oceanic lithosphere during the Late Cretaceous.
5. In Central Anatolia, the İzmir-Ankara suture is deflected southward by a major transpressive dextral shear zone, which juxtaposes the Upper Cretaceous (ca. 74 Ma) Beypazarı Granite against the Lower Karakaya Complex. The activity of this Sakarya Shear Zone is constrained between 74 and 48 Ma.
6. The subduction-accretion units and the continental crustal sequences are unconformably overlain by Lower Eocene continental to shallow marine sedimentary rocks, which provide an upper time limit for the continental collision between the Pontides and the Anatolide-Tauride Block. Sedimentary records of the Pontide margin indicate that the hard collision occurred in the Paleocene.
7. Early models for the geological evolution of Anatolia involved scenarios similar to the Alps with opening and closure of relatively small oceanic basins (e.g., Şengör & Yılmaz, 1981). Data obtained since then indicate that a Franciscan or Makran type long-ranging subduction is a better comparison for the evolution of the İzmir-Ankara ocean.

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## References

- Akdoğan, R., Okay, A. I., & Dunkl, I. (2018). Triassic-Jurassic arc magmatism in the Pontides as revealed by the U-Pb detrital zircon ages in the Jurassic sandstones, northeastern Turkey. *Turkish Journal of Earth Sciences*, 27, 89–109.
- Akdoğan, R., Okay, A. I., Sunal, G., Tari, G., Meinhold, G., & Kylander-Clark, A. R. C. (2017). Provenance of a large Lower Cretaceous turbidite submarine fan on the active Laurasian margin. *Journal of Asian Earth Sciences*, 134, 309–329.
- Aksay, A., Pehlivan, Ş., Gedik, İ., Bilginer, E., Duru, M., Akbaş, B., & Altun, İ. (2002). *Geological map of Turkey, Zonguldak sheet, 1: 500 000 scale*. Ankara: Maden Tetkik ve Arama Genel Müdürlüğü.
- Altın, D., Koçyiğit, A., Farinacci, A., Nicosia, U., & Conti, M. A. (1991). Jurassic-Lower Cretaceous stratigraphy and paleogeographic evolution of the southern part of North-Western Anatolia. *Geologica Romana*, 27, 13–80.
- Altın, E. (1976). Geology of the northern portion of the Middle Sakarya River. *İstanbul Üniversitesi Fen Fakültesi Mecmuası, Seri B*, 41, 35–56.
- Aygül, M., Okay, A. I., Oberhänsli, R., & Sudo, M. (2016). Pre-collisional accretionary growth of the southern Laurasian margin, Central Pontides, Turkey. *Tectonophysics*, 671, 218–234.
- Barrier, E., & Vrielynck, B. (2008). Atlas of paleotectonic maps of the Middle East. Commission for the Geological Map of the World, <https://ccgm.org/en/home/154-atlas-of-paleotectonic-maps-of-the-middle-east-mebe-program-9782917310007.html>.
- Bortolotti, V., Chiari, M., Göncüoğlu, M. C., Principi, G., Saccani, E., Tekin, U. K., & Tassinari, R. (2018). The Jurassic–Early Cretaceous basalt–chert association in the ophiolites of the Ankara Mélange, east of Ankara, Turkey: Age and geochemistry. *Geological Magazine*, 155, 451–478.



- Bozkurt, E., Okay, A. I., & Gerdes, A. (2019). Maximum depositional age and tectonic significance of the rocks of the Tavşanlı Zone: Evidence from U-Pb detrital zircon geochronology. *72nd Geological Congress of Turkey, 28.01-01.02.2019 Ankara, Abstract book*, 440–441.
- Bragin, N. Y., & Tekin, U. K. (1996). Age of radiolarian chert blocks from the Senonian ophiolitic mélange (Ankara, Turkey). *Island Arc*, 5, 114–122.
- Brown, D., Ryan, P. D., Afonso, J. C., Boutelier, D., Burg, J. P., Byrne, T., et al. (2011). Arc-continent collision: The making of an orogeny. In D. Brown, & P. D. Ryan (Eds.), *Arc-continent collision*, (pp. 477–493). Berlin: Springer-Verlag.
- Çelik, Ö. F., Marzoli, A., Marschik, R., Chiaradia, M., Neubauer, F., & Öz, İ. (2011). Early–Middle Jurassic intra-oceanic subduction in the İzmir-Ankara Ocean, Northern Turkey. *Tectonophysics*, 539, 120–134.
- Çetinkaplan, M., Candan, O., Oberhänsli, R., & Bousquet, R. (2008). Pressure–temperature evolution of lawsonite eclogite in Sivrihisar; Tavşanlı Zone–Turkey. *Lithos*, 104, 12–32.
- Çoğulu, E. (1967). Etude pétrographique de la région de Mihaliççik (Turquie). *Schweizerische Mineralogische und Petrographische Mitteilungen*, 47, 683–824.
- Davis, P. B., & Whitney, D. L. (2006). Petrogenesis of lawsonite and epidote eclogite and blueschist, Sivrihisar Massif, Turkey. *Journal of Metamorphic Geology*, 24, 823–849.
- Dilek, Y., & Thy, P. (2006). Age and petrogenesis of plagiogranite intrusion in the Ankara mélange, central Turkey. *Island Arc*, 15, 44–57.
- Göncüoğlu, M. C., Turhan, N., Şentürk, K., Özcan, A., Uysal, Ş., & Yalınız, M. K. (2000). A geotraverse across northwestern Turkey: Tectonic units of the Central Sakarya region and their tectonic evolution. In E. Bozkurt, J. A. Winchester, & J. D. A. Piper (Eds.), *Tectonics and magmatism in Turkey and the surrounding area, Special Publications*, (Vol. 173, pp. 139–162). London: Geological Society.
- Göncüoğlu, M. C., Yalınız, M. K., & Tekin, U. K. (2006). Geochemistry, tectono-magmatic discrimination and radiolarian ages of basic extrusives within the İzmir-Ankara suture belt (NW Turkey): Time constraints for the Neotethyan evolution. *Ophioliti*, 31, 25–38.
- Helvacı, C., Öztürk, Y. Y., Satır, M., & Shang, C. K. (2014). U-Pb zircon and K-Ar geochronology reveal the emplacement and cooling history of the Late Cretaceous Beypazarı granitoid, Central Anatolia, Turkey. *International Geology Review*, 56, 1138–1155.
- Kasapoğlu, B., Ersoy, Y. E., Uysal, İ., Palmer, M. R., Zack, T., Koralay, E. O., & Karlsson, A. (2016). The petrology of Paleogene volcanism in the Central Sakarya, Nallıhan Region: Implications for the initiation and evolution of post-collisional, slab break-off-related magmatic activity. *Lithos*, 246–247, 81–98.
- Kaya, O., & Mostler, H. (1992). A Middle Triassic age for low-grade greenschist facies metamorphic sequence in Bergama (İzmir), western Turkey: The first paleontological age assignment and structural-stratigraphic implications. *Newsletters on Stratigraphy*, 26, 1–17.
- Kibici, Y., İlbeli, N., Yıldız, A., & Bağcı, M. (2010). Geochemical constraints on the genesis of the Sarıcakaya intrusive rocks, Turkey: Late Paleozoic crustal melting in the central Sakarya Zone. *Chemie der Erde-Geochemistry*, 70, 243–256.
- Konak, N. (2002). *Geological map of Turkey, İzmir sheet 1:500,000 scale*. Ankara: Maden Tetkik ve Arama Genel Müdürlüğü.
- Kozur, H., Aydın, M., Demir, O., Yakar, H., Göncüoğlu, M. C., & Kuru, F. (2000). New stratigraphic and palaeogeographic results from the Palaeozoic and early Mesozoic of the Middle Pontides (northern Turkey) in the Azdavay, Devrekani, Küre and İnebolu areas. Implications for the Carboniferous–Early Cretaceous geodynamic evolution and some related remarks to the Karakaya oceanic rift basin. *Geologia Croatica*, 53, 209–268.
- Kozur, H., & Kaya, O. (1994). First evidence of pelagic Late Permian conodonts from NW Turkey. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte*, 339–347.
- Kozur, H., Kaya, O., & Mostler, H. (1996). First evidence of lower to middle Scythian (Dienerian - lower Olenekian) radiolarians from the Karakaya zone of northwestern Turkey. *Geologisch-Paläontologische Mitteilungen Universität Innsbruck, Sonderband*, 4, 271–285.
- Kylander-Clark, A. R. C., Hacker, B. R., & Cottle, J. M. (2013). Laser-ablation split-stream ICP petrochronology. *Chemical Geology*, 345, 99–112.
- Maden Tetkik ve Arama Genel Müdürlüğü (2016). *Geological map of Turkey, 1:1,000,000 scale*, Ankara.
- Moores, E. M. (1981). Ancient suture zones within continents. *Science*, 213, 41–46.
- Mueller, M. A., Licht, A., Campbell, C., Ocakoğlu, F., Taylor, M. H., Burch, L., et al. (2019). Collision chronology along the İzmir-Ankara-Erzincan suture zone: Insights from the Sarıcakaya Basin, western Anatolia. *Tectonics*, 38, 3652–3674. <https://doi.org/10.1029/2019TC005683>
- Ocakoğlu, F., Hakyemez, A., Açıkalın, S., Özkan Altuner, S., BüyükmERIC, Y., Licht, A., et al. (2019). Chronology of subduction and collision along the İzmir-Ankara suture in Western Anatolia: Records from the central Sakarya Basin. *International Geology Review*, 61, 1244–1269.
- Okay, A. I. (2000). Was the Late Triassic orogeny in Turkey caused by the collision of an oceanic plateau? In E. Bozkurt, J. A. Winchester, & J. D. A. Piper (Eds.), *Tectonics and magmatism in Turkey and surrounding area, Special Publication*, (Vol. 173, pp. 25–41). London: Geological Society.
- Okay, A. I., Altuner, D., & Kylander-Clark, A. R. C. (2019). Major Late Cretaceous mass flows in central Turkey recording the disruption of the Mesozoic continental margin. *Tectonics*, 38, 960–989. <https://doi.org/10.1029/2018TC005076>
- Okay, A. I., Altuner, D., Sunal, G., Tüysüz, O., Aygül, M., Akdoğan, R., et al. (2018). Geological evolution of the central Pontides. In M. D. Simmons, G. C. Tari, & A. I. Okay (Eds.), *Petroleum geology of the Black Sea, Special Publication*, (Vol. 464, pp. 33–67). London: Geological Society.
- Okay, A. I., & Göncüoğlu, M. C. (2004). Karakaya complex: A review of data and concepts. *Turkish Journal of Earth Sciences*, 13, 77–95.
- Okay, A. I., Harris, N. B. W., & Kelley, S. P. (1998). Exhumation of blueschists along a Tethyan suture in northwest Turkey. *Tectonophysics*, 285, 275–299.
- Okay, A. I., & Monié, P. (1997). Early Mesozoic subduction in the Eastern Mediterranean: Evidence from Triassic eclogite in northwest Turkey. *Geology*, 25, 595–598.
- Okay, A. I., Monod, O., & Monié, P. (2002). Triassic blueschists and eclogites from northwest Turkey: Vestiges of the Paleo-Tethyan subduction. *Lithos*, 64, 155–178.
- Okay, A. I., & Mostler, H. (1994). Carboniferous and Permian radiolarite blocks from the Karakaya Complex in northwest Turkey. *Turkish Journal of Earth Sciences*, 3, 23–28.
- Okay, A. I., & Nikishin, A. M. (2015). Tectonic evolution of the southern margin of Laurasia in the Black Sea region. *International Geology Review*, 57, 1051–1076.
- Okay, A. I., Noble, P. J., & Tekin, U. K. (2011). Devonian radiolarian ribbon cherts from the Karakaya Complex, northwest Turkey: Implications for the Paleo-Tethyan evolution. *Comptes Rendus Palevol*, 10, 1–10.
- Okay, A. I., Sunal, G., Tüysüz, O., Sherlock, S., Keskin, M., & Kylander-Clark, A. R. C. (2014). Low-pressure–high-temperature metamorphism during extension in a Jurassic magmatic arc, Central Pontides, Turkey. *Journal of Metamorphic Geology*, 32, 49–69.

- Okay, A. I., & Tüysüz, O. (1999). Tethyan sutures of northern Turkey. In B. Durand, L. Jolivet, F. Horváth, & M. Séranne (Eds.), *The Mediterranean basins: Tertiary extension within the Alpine orogen, Special Publication*, (Vol. 156, pp. 475–515). London: Geological Society.
- Okay, A. I., & Whitney, D. L. (2010). Blueschists, eclogites, ophiolites and suture zones in northwest Turkey: A review and a field excursion guide. *Ophioliti*, 35, 131–172.
- Öztürk, Y. Y., Helvacı, C., & Satır, M. (2012). Geochemical and isotopic constraints on petrogenesis of the Beypazarı Granitoid, NW Ankara, western central Anatolia, Turkey. *Turkish Journal of Earth Sciences*, 21, 53–77.
- Passchier, C. W., & Trouw, R. A. J. (1998). *Micro-tectonics*, (p. 289). Berlin: Springer Verlag.
- Pickett, E., & Robertson, A. H. F. (2004). Significance of the Triassic volcanogenic Nilüfer Unit for Paleotethys and the Karakaya suture zone in NW Turkey. *Turkish Journal of Earth Sciences*, 13, 97–143.
- Plunder, A., Agard, P., Chopin, C., Pourteau, A., & Okay, A. I. (2015). Accretion, underplating and exhumation along a subduction interface: From subduction initiation to continental subduction (Tavşanlı zone, W. Turkey). *Lithos*, 226, 233–254.
- Plunder, A., Agard, P., Chopin, C., Soret, M., Okay, A. I., & Whitechurch, H. (2016). Metamorphic sole formation, emplacement and blueschist overprint: Early obduction dynamics witnessed by Western Turkey ophiolites. *Terra Nova*, 28, 329–339.
- Pourteau, A., Scherer, E. E., Schorn, S., Bast, R., Schmidt, A., & Ebert, L. (2019). Thermal evolution of an ancient subduction interface revealed by Lu-Hf garnet geochronology, Halilbağı Complex (Anatolia). *Geoscience Frontiers*, 10, 127–148.
- Rojay, B. (2013). Tectonic evolution of the Cretaceous Ankara Ophiolitic Mélange during the Late Cretaceous to pre-Miocene interval in central Anatolia, Turkey. *Journal of Geodynamics*, 65, 66–81.
- Rojay, B., Altıner, D., Özkan-Altıner, S., Önen, A. P., James, S., & Thirlwall, M. F. (2004). Geodynamic significance of the Cretaceous pillow basalts from North Anatolian Ophiolitic Melange Belt (Central Anatolia, Turkey): Geochemical and paleontological constraints. *Geodinamica Acta*, 17, 349–361.
- Şahin, M., Yaltırak, C., & Karacık, Z. (2019). A case study of compression to escape tectonic transition: Tectonic evolution of the Nallıhan Wedge and comparison with the Tercan Wedge (Eastern Mediterranean, Turkey). *Journal of Asian Earth Sciences*, 174, 311–331.
- Saner, S. (1980). Paleogeography and depositional features of the Jurassic and younger sediments of the Mudurnu-Göynük basin (in Turkish). *Türkiye Jeoloji Kurumu Bülteni*, 23, 39–52.
- Sarıfakıoğlu, E., Dilek, Y., & Sevin, M. (2014). Jurassic–Paleogene intraoceanic magmatic evolution of the Ankara Mélange, north-central Anatolia, Turkey. *Solid Earth*, 5, 77–108.
- Schmid, S. M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., et al. (2008). The Alpine-Carpathian-Dinaridic orogenic system: Correlation and evolution of tectonic units. *Swiss Journal of Geosciences*, 101, 139–183.
- Şengör, A. M. C. (1985). The story of Tethys: How many wives did Okeanos have? *Episodes*, 8, 3–12.
- Şengör, A. M. C., & Yılmaz, Y. (1981). Tethyan evolution of Turkey, a plate tectonic approach. *Tectonophysics*, 75, 181–241.
- Şengör, A. M. C., Yılmaz, Y., & Sungurlu, O. (1984). Tectonics of the Mediterranean Cimmerides: Nature and evolution of the western termination of Palaeo-Tethys. In J. E. Dixon, & A. H. F. Robertson (Eds.), *Geological evolution of the Eastern Mediterranean, Special Publications*, (Vol. 17, pp. 77–112). London: Geological Society.
- Sherlock, S., Kelley, S. P., Inger, S., Harris, N., & Okay, A. I. (1999). <sup>40</sup>Ar–<sup>39</sup>Ar and Rb–Sr geochronology of high-pressure metamorphism and exhumation history of the Tavşanlı Zone, NW Turkey. *Contributions to Mineralogy and Petrology*, 137, 46–58.
- Speciale, P. A., Catlos, E. J., Yıldız, G. O., Shin, T. A., & Black, K. N. (2014). Zircon ages from the Beypazarı granitoid pluton (north central Turkey): Tectonic implications. *Geodinamica Acta*, 25, 162–182.
- Stern, C. R. (2011). Subduction erosion: Rates, mechanisms, and its role in arc magmatism and the evolution of the continental crust and mantle. *Gondwana Research*, 20, 284–308.
- Tekin, U. K., Göncüoğlu, M. C., & Turhan, N. (2002). First evidence of Late Carnian radiolarians from the İzmir-Ankara suture complex, central Sakarya, Turkey: Implications for the opening age of the İzmir-Ankara branch of Neo-Tethys. *Geobios*, 35, 127–135.
- Topuz, T., Candan, O., Okay, A. I., von Quadt, A., Othman, M., Zack, T., & Wang, J. (2020). Silurian anorogenic basic and acidic magmatism in Northwest Turkey: Implications for the opening of the Paleo-Tethys. *Lithos*, 356–357, 105302.
- Topuz, T., Göçmengil, G., Rolland, Y., Çelik, Ö. F., Zack, T., & Schmitt, A. K. (2013). Jurassic accretionary complex and ophiolite from northeast Turkey: No evidence for the Cimmerian continental ribbon. *Geology*, 41, 255–258.
- Topuz, T., Okay, A. I., Schwarz, W. H., Sunal, G., Altherr, R., & Kylander-Clark, A. R. C. (2018). A middle Permian ophiolite fragment in Late Triassic greenschist- to blueschist-facies rocks in NW Turkey: An earlier pulse of suprasubduction-zone ophiolite formation in the Tethyan belt. *Lithos*, 300–301, 121–135.
- Turhan, N. (2002). *Geological map of Turkey, Ankara sheet 1:500,000 scale*. Ankara: Maden Tetkik ve Arama Genel Müdürlüğü.
- Türkecan, A., & Yurtsever, A. (2002). *Geological map series of Turkey, Istanbul sheet, 1:500,000 scale*. Ankara: Maden Tetkik ve Arama Genel Müdürlüğü.
- Ustaömer, P. A., Ustaömer, T., & Robertson, A. H. F. (2012). Ion probe U–Pb dating of the Central Sakarya basement: A peri-Gondwana terrane intruded by late Lower Carboniferous subduction/collision-related granitic rocks. *Turkish Journal of Earth Sciences*, 21, 905–932.
- Ustaömer, T., Ustaömer, P. A., Robertson, A. H. F., & Gerdes, A. (2016). Implications of U–Pb and Lu–Hf isotopic analysis of detrital zircons for the depositional age, provenance and tectonic setting of the Permian–Triassic Palaeotethyan Karakaya Complex, NW Turkey. *International Journal of Earth Sciences*, 105, 7–38.
- Wakabayashi, J. (2015). Anatomy of a subduction complex: Architecture of the Franciscan Complex, California, at multiple length and time scales. *International Geology Review*, 57, 669–746.
- Widiyantoro, S., & van der Hilst, R. (1996). Structure and evolution of lithospheric slab beneath the Sunda Arc, Indonesia. *Science*, 271, 1566–1570.
- Yılmaz, Y. (2017). Major problems of western Anatolian geology. *Active Global Seismology: Neotectonics and Earthquake Potential of the Eastern Mediterranean Region, Geophysical Monograph*, 225, 141–188.